International Journal of Thermal Sciences 80 (2014) 33–40

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Simulation of the response of a thermosyphon under pulsed heat input conditions

Khurram Kafeel*, Ali Turan

School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, P.O. Box 88, Manchester M60 1QD, UK

ARTICLE INFO

Article history:
Received 15 June 2013
Received in revised form
22 January 2014
Accepted 22 January 2014
Available online 4 March 2014

Keywords:
Multiphase
Thermosyphon
Heat and mass transfer
Evaporation
Condensation

ABSTRACT

A vertical two phase closed thermosyphon is analyzed numerically using the two-fluid methodology within Eulerian multiphase domain. The steadily operating thermosyphon is first simulated using a full scale axi-symmetric model. The model is then used to predict the behaviour of the thermosyphon under different pulsed heat increment conditions. The effects of evaporation, condensation and interfacial heat and mass transfer are taken into account within the two phase domain. The cooling water jacket is also modelled along with the wall of thermosyphon to simulate the effect of conjugate heat transfer between the wall and fluid phase. Results obtained show in detail the overall thermal response of the thermosyphon along with the dynamics of fluid flow within its core. It is established that two-fluid methodology along with the applied techniques can be used effectively for the purpose of simulation of two phase system like a typical thermosyphon.

1. Introduction

The idea of using passive devices for the removal of heat was first coined in early 40 s and after by Gaugler [1] and Grover [2]. Since then, heat pipes have become an integral part of many modern thermal engineering systems. A passive device like a heat pipe is one which requires no power source to transfer heat between its source and sink. Their effectiveness as a two-phase heat removal device comes from the use of latent heat of working fluid they contain. The absorption and release of heat between phases within a heat pipe provides thermal conductivity levels greatly exceeding that of any known metal (ref. [3]). A typical heat pipe is of the form of a closed cylinder consisting of a condenser section at the bottom, an evaporator section at the top and an adiabatic section in between them. The inner surface of the heat pipe wall holds special wick material which is used to transfer the condensate from the evaporator back to the condenser section at the top. The capillary force of the wicking material is used to transfer working fluid against gravity. Thermosyphones are special types of heat pipes having no wicking material; instead, thermosyphones use gravity for the condensate return to the evaporator and therefore they have the evaporator section at their bottom and condensing section at the top. Heat absorbed at the evaporator changes the working fluid from liquid to gas phase which moves towards the condenser where it is released and the working fluid changes phase from gas to liquid. This liquid condensate is transferred back to the evaporator via gravity in thermosyphones.

Due to their effectiveness as a passive heat removal device, heat pipes and thermosyphones have found their application within a large range of thermal engineering applications like heat exchangers [4], solar systems [5], electronics industry [6], space applications [7] etc. Their simple design, cost effectiveness, reliability and durability have made them very attractive for many industrial applications.

Experimental and numerical investigations have been conducted by many researchers to find out the operational characteristics of thermosyphones and heat pipes. Noie [8] in his experiment, investigated the effects of heat input level, fill ratio and aspect ratio on the performance of a two-phase closed thermosyphon. Effects of cross-sectional area on the performance of thermosyphon were investigated experimentally by Amatachaya et al. [9]. In their research they used two different cross sectional geometries for the thermosyphon, one was circular and the other flat. Jian Ling et al. [10], performed experiments on a radially rotating thermosyphon under high temperature environment to investigate the suitability of thermosyphon for turbine blade cooling. In this model, centrifugal force created by radial rotation was used to return the condensate to evaporator. Many numerical investigations have also been performed, apart from experimental investigations,

---

* Corresponding author. Tel.: +44 (0)7901035960 (mobile).
E-mail addresses: khurram.kafeel@postgrad.manchester.ac.uk, khurram464@hotmail.com (K. Kafeel), A.Turan@manchester.ac.uk (A. Turan).

http://dx.doi.org/10.1016/j.ijthermalsci.2014.01.020
1290-0729/

Nomenclature

c	relaxation parameter, s^{-1}
g	gravitational acceleration, m s^{-2}
H	interfacial heat transfer coefficient, W m^{-3} K^{-1}
h	specific enthalpy, J kg^{-1}
L	latent heat, J kg^{-1}
$\dot{m}$	interfacial mass transfer, kg m^{-3} s^{-1}
p	pressure, kg m^{-1} s^{-2}
q	heat flux, J m^{-2} s^{-1}
S	mass source term, kg m^{-3} s^{-1}
t	time, s
T	temperature, K
v	velocity, m s^{-1}
V	cell volume, m^3

Greek symbols

α	volume fraction
β	thermal expansion coefficient, K^{-1}
ρ	density, kg m^{-3}

Subscripts

a	general phase
eff	effective
l	liquid phase
lv	liquid–vapour
m	phase mixture
o	operating conditions
v	vapour
vl	vapour–liquid
sat	saturation

to analyze the behaviour of heat pipes and thermosyphones. Numerical modelling of steady-state two phase closed thermosyphon was conducted by Zuo et al. [11]. The effects of the working fluid inventory and evaporator to condenser length ratio was analyzed in their study. Yiding Cao and Amir Faghri [12], performed numerical calculation for a transient two dimensional heat pipe. They simulated the response of high temperature heat pipe under pulsed heat input with compressible vapour flow. Zheshu Ma et al. [13] presented their results for a closed two-phase thermosyphon subjected to different input heat flux conditions. They used IPSA (Inter Phase Slip Algorithm) algorithm to solve the governing equations for both phases. A numerical method was developed by Nouri-Borujerdi et al. [14], based on the SIMPLE algorithm. Steady state vapour flow analysis was performed under different heat addition and rejection conditions for both symmetric and asymmetric models. Tarik Kaya et al. [15], also presented their Finite Element based 3-d numerical model for the characterization of heat pipes. Temperature profiles and velocity distributions were predicted under the steady state operation of heat pipe.

Computational Fluid Dynamics (CFD) is becoming more and more helpful as a predictive tool for many heat transfer applications extremely useful for industrial purposes. Although the field of multiphase CFD is not as mature as its counterpart like single phase and turbulence etc, adequate progress has been made in the past few decades in terms of numerics of multiphase systems that has enabled the field to be on the verge of reliable prediction of many of the practical multiphase phenomena. There are many published studies regarding multiphase flow simulations involving thermal analysis. Jaroslaw Legierski et al. [16] presented their simulation of transient behaviour for an open-ended heat pipe. Volume of Fluid (VOF) [17] method was used using Fluent 6.0 software for capturing two phase flow interactions. Same methodology was employed by Asghar Alizadehdakhel et al. [18] for their steady state simulation of a closed thermosyphon. They obtained the temperature profiles along thermosyphon length, vapour fraction and velocity contour of phases within the thermosyphon. Many others (Subhashini Ghorai et al. [19], De Schepper et al. [20] etc) used the VOF method to simulate different multi fluid systems. Eulerian multiphase model, on the other hand, provides greater detail about fluid dynamics in comparison to other multiphase models such as VOF, because it solves for continuity, momentum and energy equation for each phase separately. The authors of this paper have published their result for a similar thermosyphon working under steady state and with a evaporation relaxation parameter of 0.09 s^{-1}. They also investigated the effect of relaxation parameter on the thermal hydraulics of the thermosyphon.

In the present study similar methodology is utilized to predict the behaviour of the thermosyphon with evaporation relaxation time of 0.1 s^{-1} and its transient response when subjected to different levels of pulsed heat increments. The results obtained (Section 4) from current methodology provide comprehensive response of the thermal hydraulic performance of the thermosyphon given in the form of a number of different operational parameters presented on phasic level.

2. Theory

Euler–Euler two-fluid methodology is based on the technique of averaging each phasic property within a control volume with respect to the volume fraction of that phase. The fluids are treated as interpenetrating continua, making different phases occupy same control volume depending upon their respective volume fractions. Hence, the volume fraction of different phases within a control volume equals to unity when added together. Therefore, for two phase liquid–vapour system this can be written as,

$$\alpha_l + \alpha_v = 1 \tag{1}$$

In tow-fluid methodology, the mass, momentum and energy equations are solved for each phase separately. The generalized form of conservation equations solved for each phase are provided as under.

2.1. Continuity

Liquid phase:

$$\frac{\delta}{\delta t}(\alpha_l \rho_l) + \nabla \cdot (\alpha_l \rho_l v_l) = (\dot{m}_{vl} - \dot{m}_{lv}) + S_l \tag{2}$$

Vapour phase:

$$\frac{\delta}{\delta t}(\alpha_v \rho_v) + \nabla \cdot (\alpha_v \rho_v v_v) = (\dot{m}_{lv} - \dot{m}_{vl}) + S_v \tag{3}$$

here ‘S’ is the mass source term which is equal to zero in our case while the interfacial mass transfer due to evaporation $(\dot{m}_{lv})$ and condensation $(\dot{m}_{vl})$ is modelled using the De Schepper’s [23] equation as,